Coupled Shallow - Deep Ocean Processes in the Continental Slope/Rise Regions

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LONG-TERM GOAL

Our long-term goal is to achieve a correct understanding of the physical processes at the continental margin interface, including feedbacks between the coastal and open ocean, and to investigate the ability of numerical models to simulate physical processes over continental slope regions.

OBJECTIVES

The scientific objectives of this project are placed on mechanisms by which energetic perturbations are excited by meandering of baroclinic frontal systems and/or warm-core rings approaching the shelf break from the open ocean, and how they influence the near-shore ocean circulation. Our primary task is to develop reliable predictive methods for the Gulf Stream meanders and eddies over the continental slope/rise.

APPROACH

Our approach combines theoretical investigation and analyses of existing observations with advanced numerical modeling to gain understanding and efficient representation of the most important physical processes in the littoral zone. This is a truly collaborative ONR-supported study at URI with the Dr. R. Watts and his graduate student, O. Logoutov.

WORK COMPLETED

a. *Equilibration of the Gulf Stream meanders and deep eddies over a sloping bottom*

We have investigated the effects of a topographic slope on the growth of instabilities and nonlinear equilibration of meanders in a Gulf Stream–type jet using the primitive equation Princeton Ocean Model. An unperturbed jet was prescribed as a potential vorticity (PV) front in the upper thermocline overlying intermediate layers with weak PV gradients and an initially quiescent bottom layer over a positive (same sense as isopycnal tilt) cross-stream continental slope. We conducted and analyzed a series of numerical experiments with the same initial conditions over slope and flat bottoms on the beta- and f-planes.

b. *The net advective effect of a vertically sheared current on a coherent vortex*

We have analyzed nonlinear interaction of a localized vortex and vertically sheared surrounding flow using asymptotic and numerical methods in a multi-layer quasigeostrophic model on the beta-plane. The initial vortex structure was prescribed by a circular fluid PV in one or two layers with no motion in the lower layer. Development of the beta-gyres and corresponding vortex motion were calculated following the theory by Sutyrin and Morel (1997), which was generalized by taking into account the large-scale baroclinic mean flow.

c. *Potential vorticity structure across the Gulf Stream*

In collaboration with Dr. Watts' (URI) project we have identified the most essential features of PV structure across the Gulf Stream using two high-resolution CTD sections and simultaneous Pegasus direct velocity observations. In order to reduce the noise that would result from differentiating observed fields of density and velocity, we have developed a PV-gradient model which inverts the PV field into the corresponding velocity and density fields using a geostrophic adjustment procedure. A constrained fit was applied to the PV fields in such a way that the PV-gradient model produced the best agreement with the velocity and density measurements. In this study we sought to reproduce the cross-stream velocity structure using the fewest possible number of vertical layers.

d. A d*ata assimilation technique for the density and velocity fields in the Gulf Stream*

We have developed a numerical procedure to assimilate subsurface temperature and velocity data together with the stream position to initialize the realistic mean structure of the Gulf Stream in the Princeton Ocean Model. The procedure uses the Gulf Stream temporal and spatial stability in stream coordinates to produce the structure of the entire Stream from 74W to 55W, utilizing a limited number of observed cross-sections, and a satellite AVHRR-derived GS path. In particular, conservation of the cross-stream PV pattern along the GS path is assumed. Assimilation of the PV instead of temperature and velocity measurements provides a more dynamically consistent transition between the reproduced Gulf Stream system and surrounding climatological fields.

RESULTS

a. *Equilibration of the Gulf Stream meanders and deep eddies over a sloping bottom*

The results demonstrate that the introducing a small local perturbation on a jet stream induces the growth of an instability which amplifies as it propagates downstream. The three-dimensional spatio-temporal development of meanders on Gulf Stream-type jet over a *sloping* bottom is found to be similar to a baroclinic instability amplification in a simple two-layer QG model on the beta-plane with *flat* bottom. Meanders growing over a flat bottom are able to pinch off, resembling warm- and cold-core rings, while in the presence of a slopping bottom the meander amplitudes saturate, with no eddy shedding. The growth rate and group velocity are only slightly affected by a constant slope set to 0.002. Nevertheless, this relatively weak slope efficiently controls nonlinear equilibration of meanders via constraining the development of deep eddies in the baroclinically unstable jet. The main equilibration mechanism is a homogenization of the lower-layer potential vorticity by deep eddies in the vicinity of the wave packet (Figure 1).

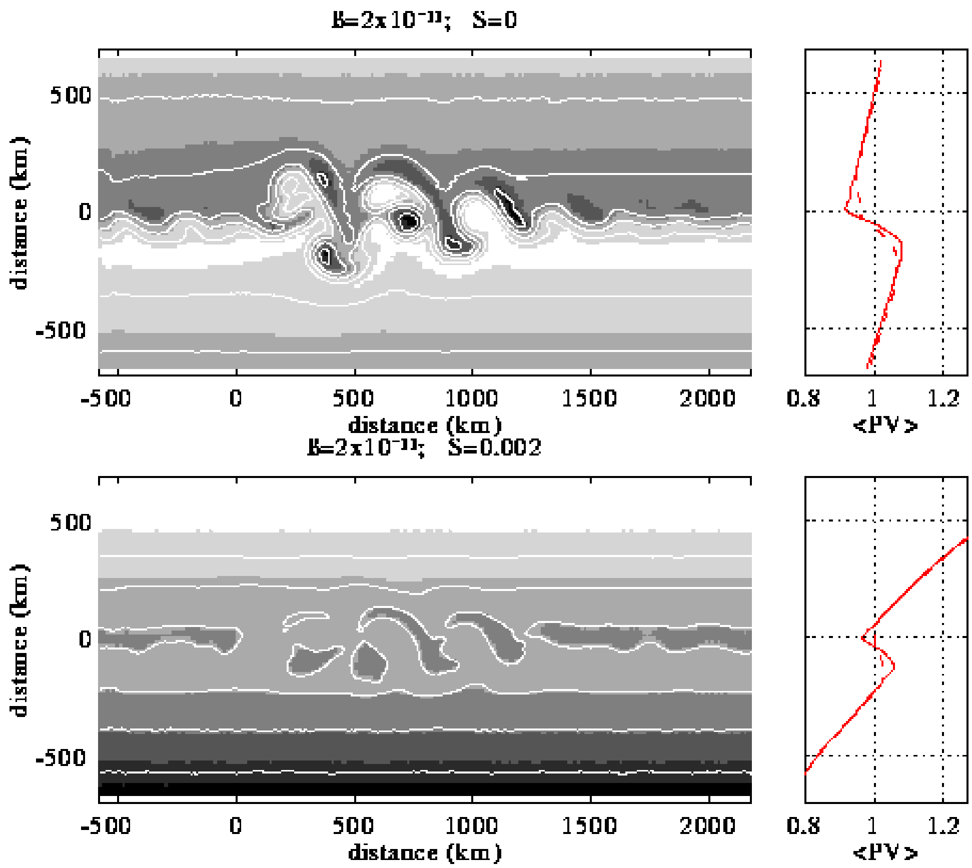

Fig. 1 Deep potential vorticity at day 40 for the flat bottom (lower panel) and sloping bottom (upper panel) cases on the β-plane. The right panels show zonally averaged deep PV profiles over the wave packet zone at day 0 (solid line) and day 40 (dashed).

A topographic slope modifies the development of deep eddies and causes the phase shift of deep eddies in the direction of the upper layer troughs/crests, thus limiting growth of the meanders. This phase-locking of the meanders with deep eddies underneath agrees qualitatively with the observational data at the SYNOP Central array (Watts et al, 1995). The equilibrated deep eddies form a mean flow that stabilizes the jet behind the packet peak. The deep flow resulted from PV mixing during the jet meandering over the continental slope is consistent with observed circulation in the Gulf Stream system. It also suggests that the deep circulation should be taken into account for realistic initialization and data assimilation of the Gulf Stream in numerical models.

b. *The net advective effect of a vertically sheared current on a coherent vortex*

Three major effects are found to contribute into the vortex translation: advection by the mean current, the beta-gyres developed due to the background PV gradient, and vertical tilting of the vortex core. Using an azimuthal mode decomposition we concluded that the trajectories of oceanic eddies (cyclones and anticyclones) in a vertically sheared current are modified due to mainly two factors: (a) rotational advection of the mean current PV, and (b) vertical coupling of tilted parts of the vortex core. We have found that the first effect compensates most of the advection by the mean current due to homogenization of PV inside the vortex core. Thus, the net advective effect of a vertically sheared current on a coherent vortex is strongly reduced the vortex is advected mainly by the planetary beta-gyres and the depth-averaged current.

c. *Potential vorticity structure across the Gulf Stream*

Two approximations of the Gulf Stream PV are suggested. The major PV front is associated with the 18° - water boundary in the Gulf Stream and by far dominates all other GS PV features.

If just the 18° - water PV front is accounted for, the basic GS structure can be reproduced, including the asymmetry of the flow, with higher shear on the cyclonic side. A more complete representation of the PV includes two additional PV-gradients in the Upper and Lower Main Thermocline, opposite to each other in direction, with a small lateral offset towards the cyclonic side of the stream with depth. This gives a considerable improvement of the velocity field in the upper Main Thermocline and reproduces the observed tilt of the flow with depth. The inverted velocity and temperature structures were also compared favorably with SYNOP moored current and temperature observations analyzed as 2-year stream-coordinate averages. This fitted PV structure remains nearly the same along stream, and taking into account PV fronts in one or three selected layers gives us a good first and second order approximations of the GS PV.

d. A d*ata assimilation technique for the density and velocity fields in the Gulf Stream*

The developed initialization procedure includes five steps:

1) Temperature and velocity data collected during the PEGASUS (1980-83) and SYNOP (1988-90) field experiments are first combined to obtain a mean quasi-geostrophic (QG) cross-stream PV structure for the Gulf Stream.

2) The mean PV structure of the entire Stream is created using the AVHRR-derived mean GS path, and assuming conservation of the cross-stream PV pattern along the path.

3) The obtained PV is then blended with the climatological PV field and the stream function corresponding to the combined PV field is calculated by solving a 3-D Poisson equation.

4) The new velocity, temperature and salinity fields are reconstructed from the obtained stream function.

5) Finally, the barotropic velocity field is corrected to reproduce increased transport downstream and the large-scale recirculation (see Fig. 2). During the test experiments, the initialized Gulf Steam system was found to remain coherent for at least several months.

IMPACT/APPLICATION

The means by which we have analyzed the evolution of baroclinic vortices and meanders over topography in this study are novel and useful for future investigations. Reduced net advective effect of a vertically sheared current on a coherent vortex and nonlinear equilibration of the Gulf Stream meanders and deep eddies over a sloping bottom have not been observed and explained previously. This has implications for our understanding of coupling, horizontal and vertical, of flow over the topography of the continental margin.

TRANSITIONS

Our approach to the potential vorticity gradient representation has been successfully used in other ONR-funded studies of the Gulf Stream structure (Watts, URI) and initialization of the Princeton Ocean Model for coupled hurricane - ocean forecasts (Ginis, URI). The developed new data assimilation scheme for Gulf Stream initialization is presently being implemented at the National Centers for Environmental Prediction under the NOPP funding (Ginis, URI).

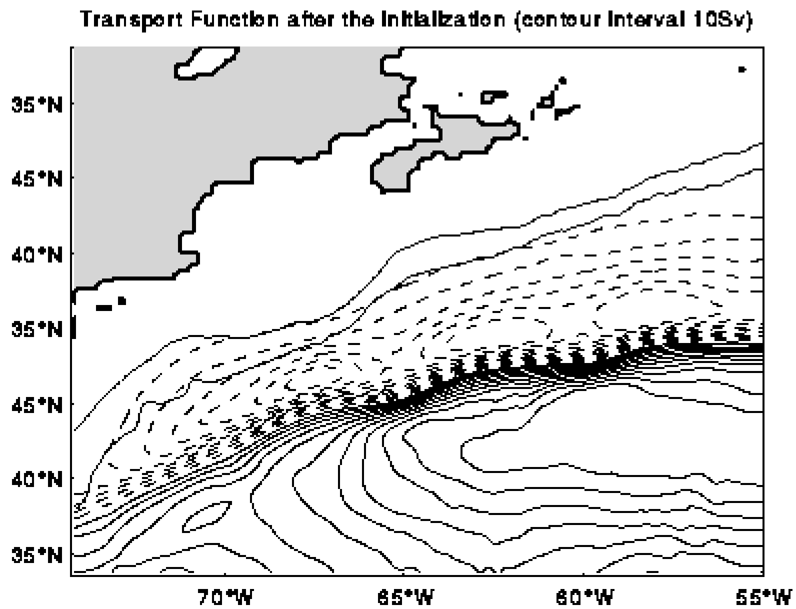

Fig.2 Streamfunction of the barotropic transport in the Gulf Stream system produced by our initialization procedure.

RELATED PROJECTS

Dr. Randy Watts (URI) uses the PV-gradient model developed in this project for analysis of the observed velocity and density structures during the SYNOP field experiment.

Drs. Isaac Ginis and Lew Rothstein (URI) use the PV initialization approach for modeling hurricane - ocean interaction.

Dr. Isaac Ginis (URI) uses the PV initialization technique in the NOPP project: Coastal Marine Demonstration of Forecast Information to Mariners for the U.S. East Coast.

Drs. Yves Morel (SHOM, France) and Georgi Sutyrin (URI) use asymptotic methods developed in this project to investigate vortex interaction with a vertically sheared surrounding flow.

Drs. Gregory Reznik (IORAS, Russia) and Georgi Sutyrin (URI) analyze mutual effects of topography and baroclinicity on long-lived vortices to improve our understanding of vertical coupling over a sloping bottom.

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